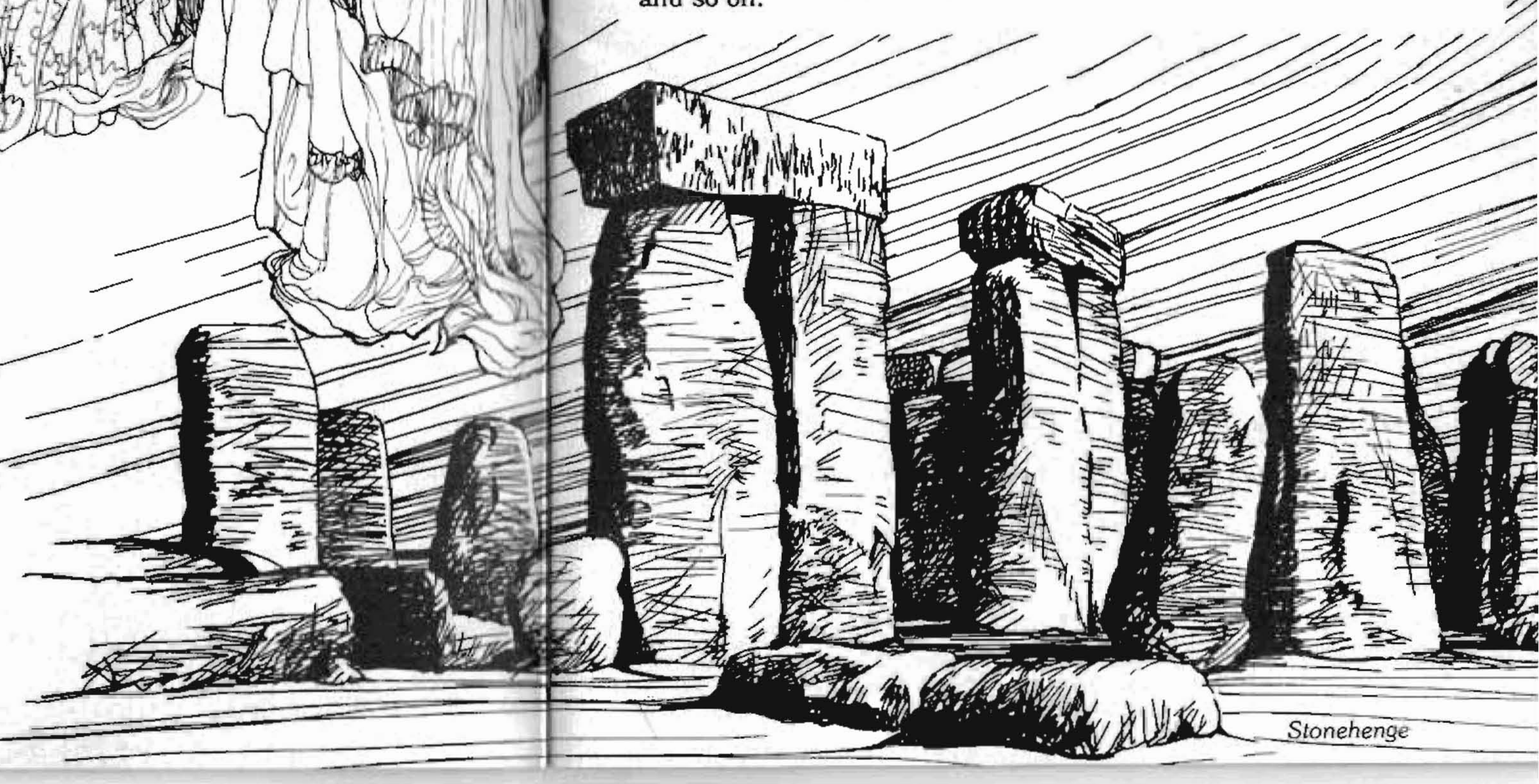

A Walk Through Time
A Journey Offered to You by
The National Institute of Standards and Technology
an agency of the Technology Administration
U.S. Department of Commerce
UNIVERSAL TIME (UTC)
MASTER CLOCK

Evolution of Time Measurement

Ancient Calendars

Celestial bodies—the sun, moon, planets, and stars—have provided us a reference for measuring the passage of time throughout our existence. Ancient civilizations relied upon the apparent motion of these bodies through the sky to determine seasons, months, and years.

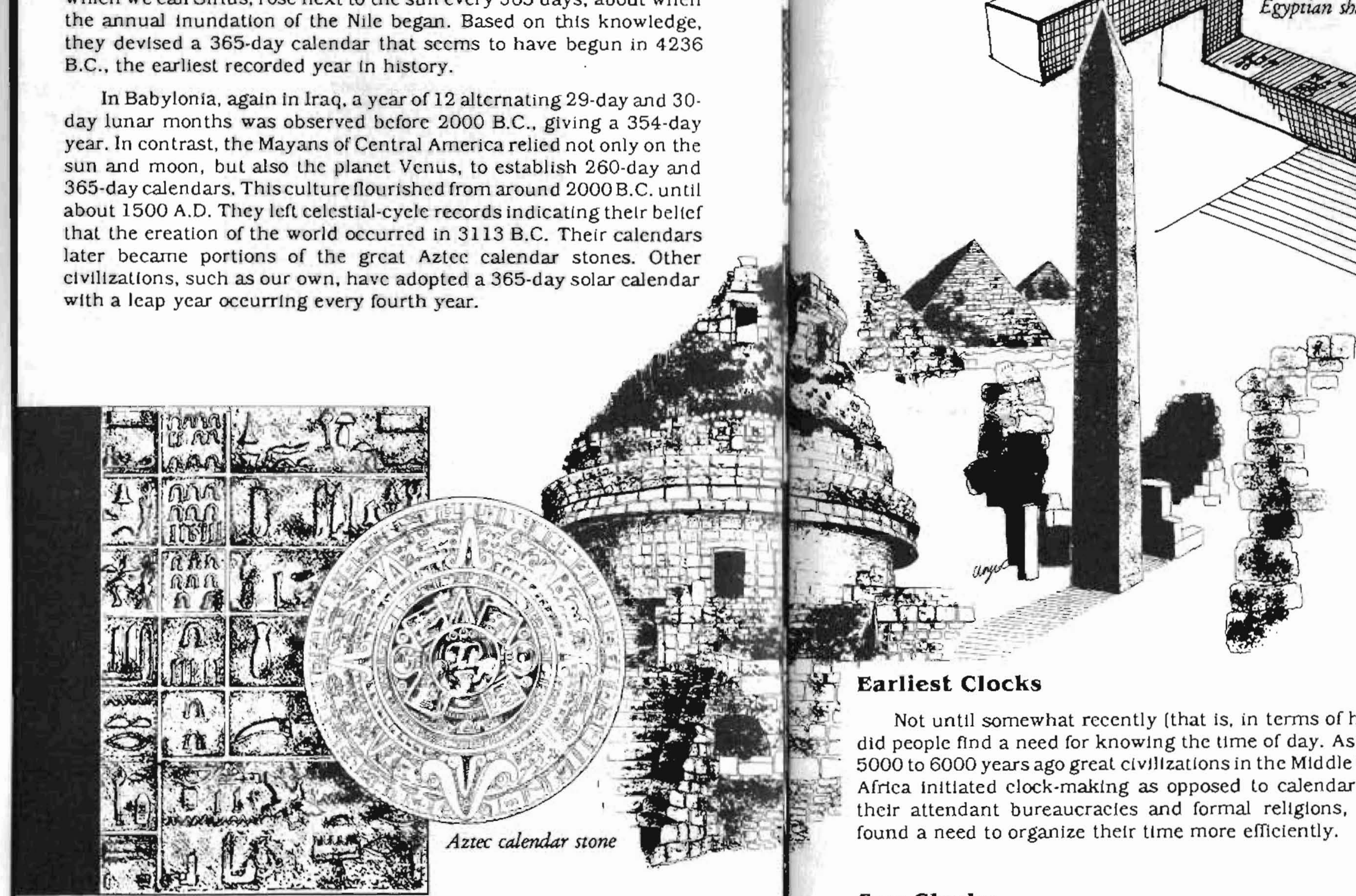
We know little about the details of timekeeping in pre-historic eras, but wherever we turn up records and artifacts, we usually discover that in every culture, some people were preoccupied with measuring and recording the passage of time. Ice-age hunters in Europe over 20,000 years ago scratched lines and gouged holes in sticks and bones, possibly counting the days between phases of the moon. Five thousand years ago, Sumerians in the Tigris-Euphrates valley in today's Iraq had a calendar that divided the year into 30-day months, divided the day into 12 periods (each corresponding to 2 of our hours), and divided these periods into 30 parts (each like 4 of our minutes). We have no written records of Stonehenge, built over 4000 years ago in England, but its alinements show its purposes apparently included the determination of seasonal or celestial events, such as lunar eclipses, solstices and so on.



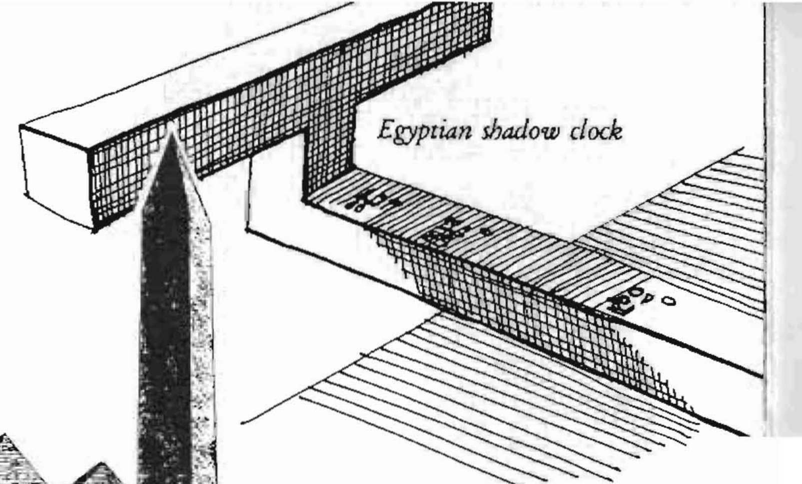
Stonehenge

The earliest Egyptian calendar was based on the moon's cycles, but later the Egyptians realized that the "Dog Star" in Canis Major, which we call Sirius, rose next to the sun every 365 days, about when the annual inundation of the Nile began. Based on this knowledge, they devised a 365-day calendar that seems to have begun in 4236 B.C., the earliest recorded year in history.

In Babylonia, again in Iraq, a year of 12 alternating 29-day and 30-day lunar months was observed before 2000 B.C., giving a 354-day year. In contrast, the Mayans of Central America relied not only on the sun and moon, but also the planet Venus, to establish 260-day and 365-day calendars. This culture flourished from around 2000 B.C. until about 1500 A.D. They left celestial-cycle records indicating their belief that the creation of the world occurred in 3113 B.C. Their calendars later became portions of the great Aztec calendar stones. Other civilizations, such as our own, have adopted a 365-day solar calendar with a leap year occurring every fourth year.



Aztec calendar stone



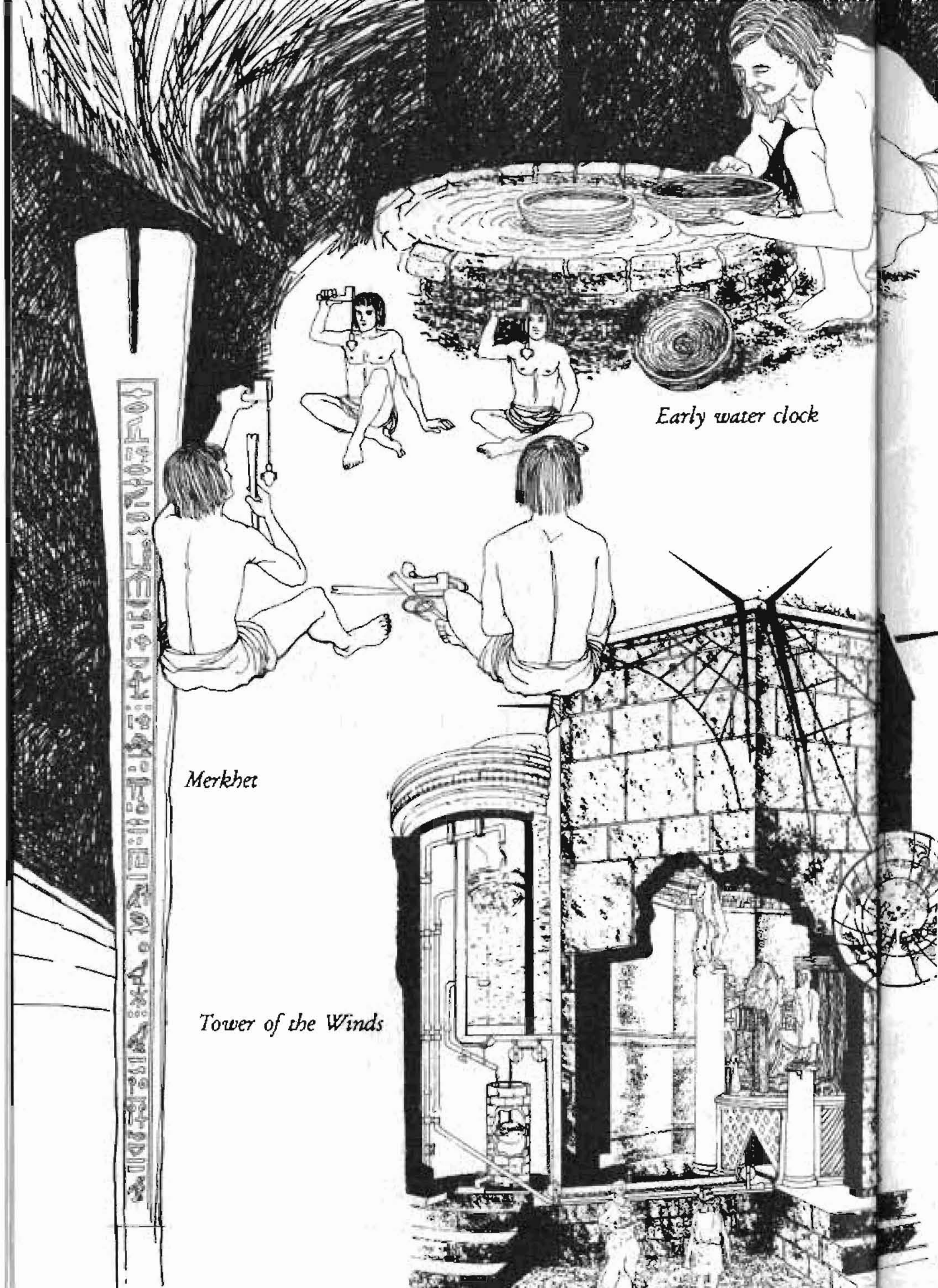
Egyptian shadow clock

Earliest Clocks

Not until somewhat recently (that is, in terms of human history) did people find a need for knowing the time of day. As best we know, 5000 to 6000 years ago great civilizations in the Middle East and North Africa initiated clock-making as opposed to calendar-making. With their attendant bureaucracies and formal religions, these cultures found a need to organize their time more efficiently.

Sun Clocks

After the Sumerian culture was lost without passing on its knowledge, the Egyptians were the next to formally divide their day into parts something like our hours. Obelisks (slender, tapering, four-sided monuments) were built as early as 3500 B.C. Their moving



shadows formed a kind of sundial, enabling citizens to partition the day into two parts by indicating noon. They also showed the year's longest and shortest days when the shadow at noon was the shortest or longest of the year. Later, markers added around the base of the monument would indicate further time subdivisions.

Another Egyptian shadow clock or sundial, possibly the first portable timepiece, came into use around 1500 B.C. to measure the passage of "hours." This device divided a sunlit day into 10 parts plus two "twilight hours" in the morning and evening. When the long stem with 5 variably spaced marks was oriented east and west in the morning, an elevated crossbar on the east end cast a moving shadow over the marks. At noon, the device was turned in the opposite direction to measure the afternoon "hours."

The *merkhet*, the oldest known astronomical tool, was an Egyptian development of around 600 B.C. A pair of merkhets were used to establish a north-south line by lining them up with the Pole Star. They could then be used to mark off nighttime hours by determining when certain other stars crossed the meridian.

In the quest for more year-round accuracy, sundials evolved from flat horizontal or vertical plates to more elaborate forms. One version was the hemispherical dial, a bowl-shaped depression cut into a block of stone, carrying a central vertical gnomon (pointer) and scribed with sets of hour lines for different seasons. The *hemicycle*, said to have been invented about 300 B.C., removed the useless half of the hemisphere to give an appearance of a half-bowl cut into the edge of a squared block. By 30 B.C., Vitruvius could describe 13 different sundial styles in use in Greece, Asia Minor, and Italy.

Elements of a Clock

Having described a variety of ways devised over the past few millennia to mark the passage of time, it is instructive to define in broad terms what constitutes a clock. All clocks must have two basic components:

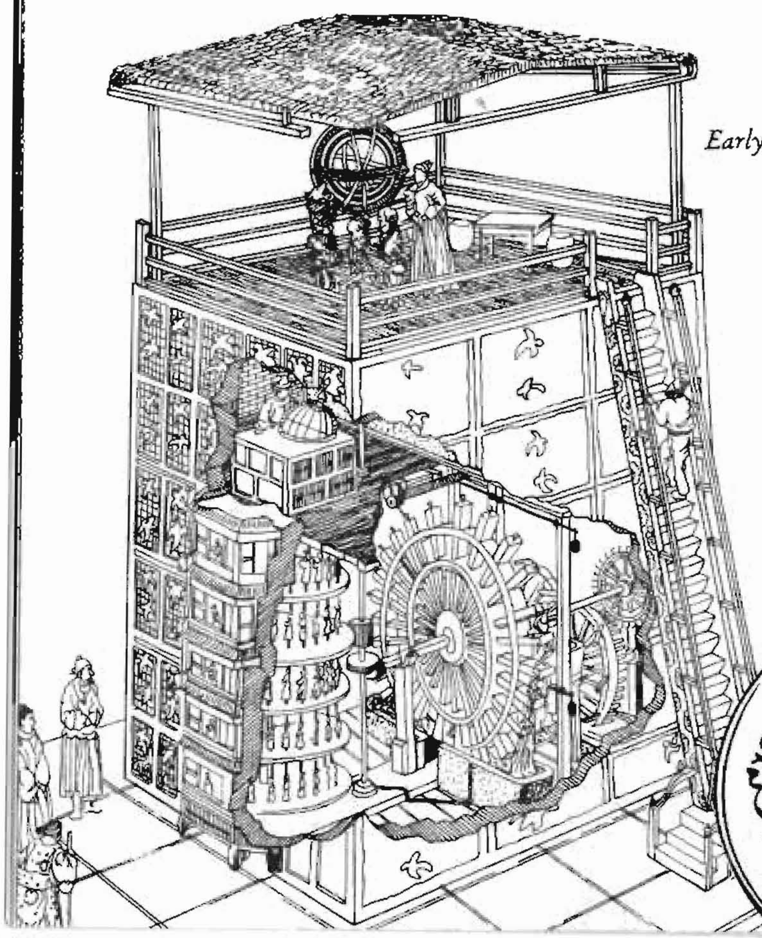
- *A regular, constant or repetitive process or action to mark off equal increments of time.* Early examples of such processes included movement of the sun across the sky, candles marked in increments, oil lamps with marked reservoirs, sand glasses ("hourglasses"), and in the Orient, small stone or metal mazes filled with incense that would burn at a certain pace.
- *A means of keeping track of the increments of time and displaying the result.* Our means of keeping track of time passage include

the position of clock hands and a digital time display.

The history of timekeeping is the story of the search for ever more consistent actions or processes to regulate the rate of a clock.

Water Clocks

Water clocks were among the earliest timekeepers that didn't depend on the observation of celestial bodies. One of the oldest was found in the tomb of Amenhotep I, buried around 1500 B.C. Later named *clepsydras* ("water thief") by the Greeks, who began using them about 325 B.C., these were stone vessels with sloping sides that allowed water to drip at a nearly constant rate from a small hole near the bottom. Other clepsydras were cylindrical or bowl-shaped containers designed to slowly fill with water coming in at a constant rate. Markings on the inside surfaces measured the passage of "hours" as the water level reached them. These clocks were used to determine hours at night, but may have been used in daylight as well. Another version consisted of a metal bowl with a hole in the bottom; when placed in a container of water the bowl would fill and sink in a certain time. These were still in use in North Africa this century.

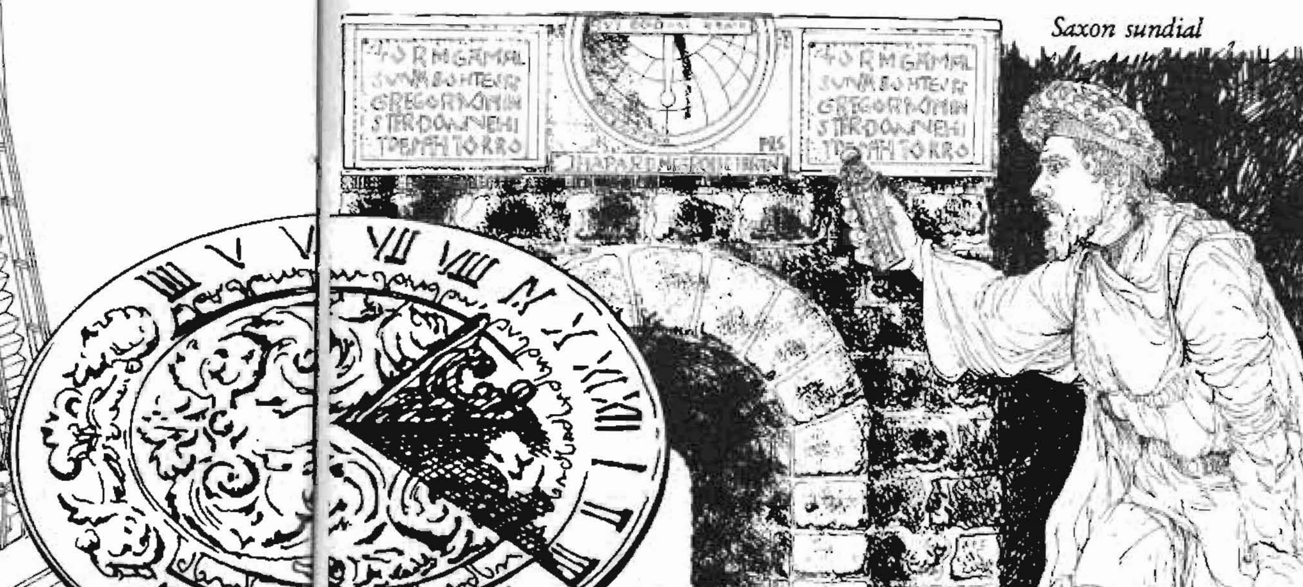


Early water clock

More elaborate and impressive mechanized water clocks were developed between 100 B.C. and 500 A.D. by Greek and Roman horologists and astronomers. The added complexity was aimed at making the flow more constant by regulating the pressure, and at providing fancier displays of the passage of time. Some water clocks rang bells and gongs, others opened doors and windows to show little figures of people, or moved pointers, dials, and astrological models of the universe.

A Greek astronomer, Andronikos, supervised the construction of the Tower of the Winds in Athens in the 1st century B.C. This octagonal structure showed scholars and marketplace shoppers both sundials and mechanical hour indicators. It featured a 24-hour mechanized clepsydra and indicators for the eight winds from which the tower got its name, and it displayed the seasons of the year and astrological dates and periods. The Romans also developed mechanized clepsydras, though their complexity accomplished little improvement over simpler methods for determining the passage of time.

In the Far East, mechanized astronomical/astrological clock-making developed from 200 to 1300 A.D. Third-century Chinese clepsydras drove various mechanisms that illustrated astronomical phenomena. One of the most elaborate clock-towers was built by Su Sung and his associates in 1088 A.D. Su Sung's mechanism incorpo-



Saxon sundial

rated a water-driven escapement invented about 725 A.D. The Su Sung clock-tower, over 30 feet tall, possessed a bronze power-driven armillary sphere for observations, an automatically rotating celestial globe, and five front panels with doors that permitted the viewing of changing mannikins which rang bells or gongs, and held tablets indicating the hour or other special times of the day.

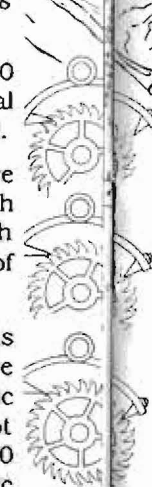
Since the rate of flow of water is very difficult to control accurately, a clock based on that flow can never achieve excellent accuracy. People were naturally led to other approaches.

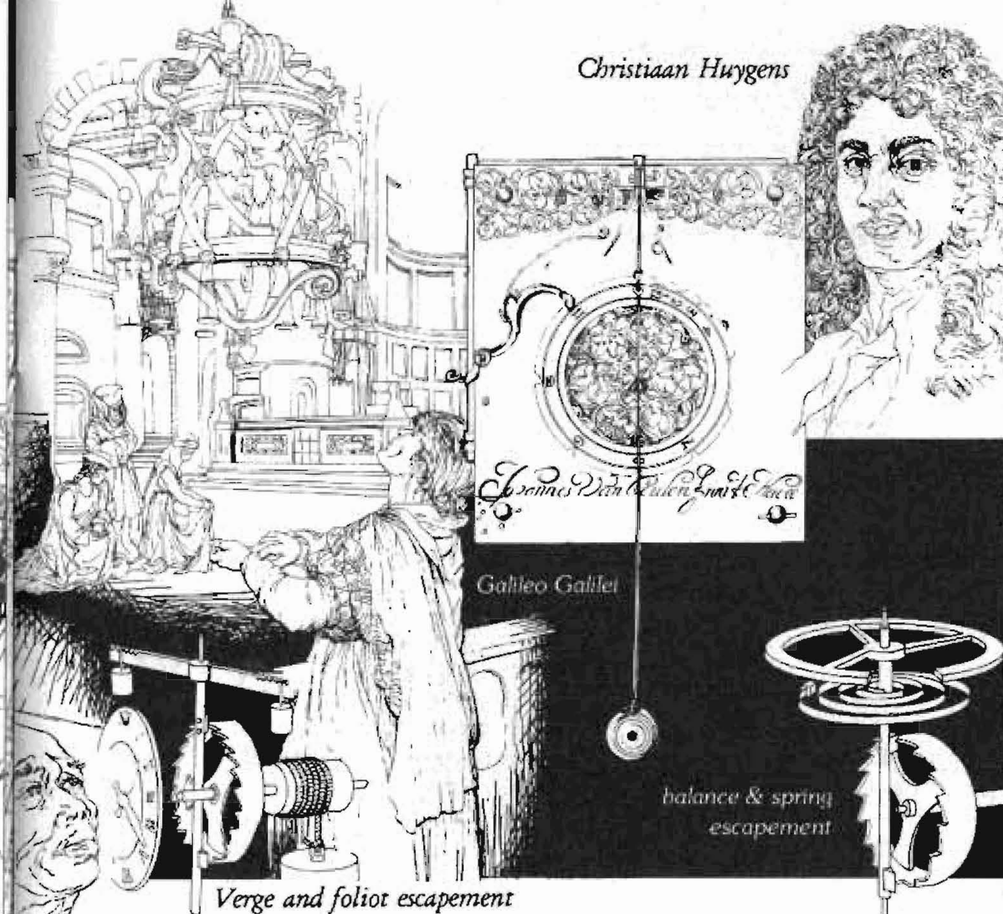
A Revolution in Timekeeping

In Europe during most of the Middle Ages (roughly 500 to 1500 A.D.), technological advancement was at a virtual standstill. Sundial styles evolved, but didn't move far from ancient Egyptian principles.

During these times, simple sundials placed above doorways were used to identify midday and four "tides" of the sunlit day. By the 10th Century, several types of pocket sundials were used. One English model identified tides and even compensated for seasonal changes of the sun's altitude.

Then, in the early-to-mid-14th century, large mechanical clocks began to appear in the towers of several large Italian cities. We have no evidence or record of the working models preceding these public clocks that were weight-driven and regulated by a verge-and-foliot escapement. Verge-and-foliot mechanisms reigned for more than 300 years with variations in the shape of the foliot. All had the same basic problem: the period of oscillation of this escapement depended heavily





on the amount of driving force and the amount of friction in the drive. Like water flow, the rate was difficult to regulate.

Another advance was the invention of spring-powered clocks between 1500 and 1510 by Peter Henlein of Nuremberg. Replacing the heavy drive weights permitted smaller (and portable) clocks and watches. Although they slowed down as the mainspring unwound, they were popular among wealthy individuals due to their size and the fact that they could be put on a shelf or table instead of hanging from the wall. These advances in design were precursors to truly accurate timekeeping.

Accurate Mechanical Clocks

In 1656, Christiaan Huygens, a Dutch scientist, made the first pendulum clock, regulated by a mechanism with a "natural" period of oscillation. Although Galileo Galilei, sometimes credited with inventing the pendulum, studied its motion as early as 1582, Galileo's design for a clock was not built before his death. Huygen's pendulum clock had an error of less than 1 minute a day, the first time such accuracy had been achieved. His later refinements reduced his clock's errors to less than 10 seconds a day.

Around 1675 Huygens developed the balance wheel and spring assembly, still found in some of today's wrist watches. This improvement allowed 17th century watches to keep time to 10 minutes a day. And in London in 1671 William Clement began building clocks with the new "anchor" or "recoil" escapement, a substantial improvement over the verge because it interferes less with the motion of the pendulum.

In 1721 George Graham improved the pendulum clock's accuracy to 1 second a day by compensating for changes in the pendulum's length due to temperature variations. John Harrison, a carpenter and self-taught clock-maker, refined Graham's temperature compensation techniques and added new methods of reducing friction. By 1761 he had built a marine chronometer with a spring and balance wheel escapement that won the British government's 1714 prize (of over $2,000,000 in today's currency) offered for a means of determining longitude to within one-half degree after a voyage to the West Indies. It kept time on board a rolling ship to about one-fifth of a second a day, nearly as well as a pendulum clock could do on land, and 10 times better than required.

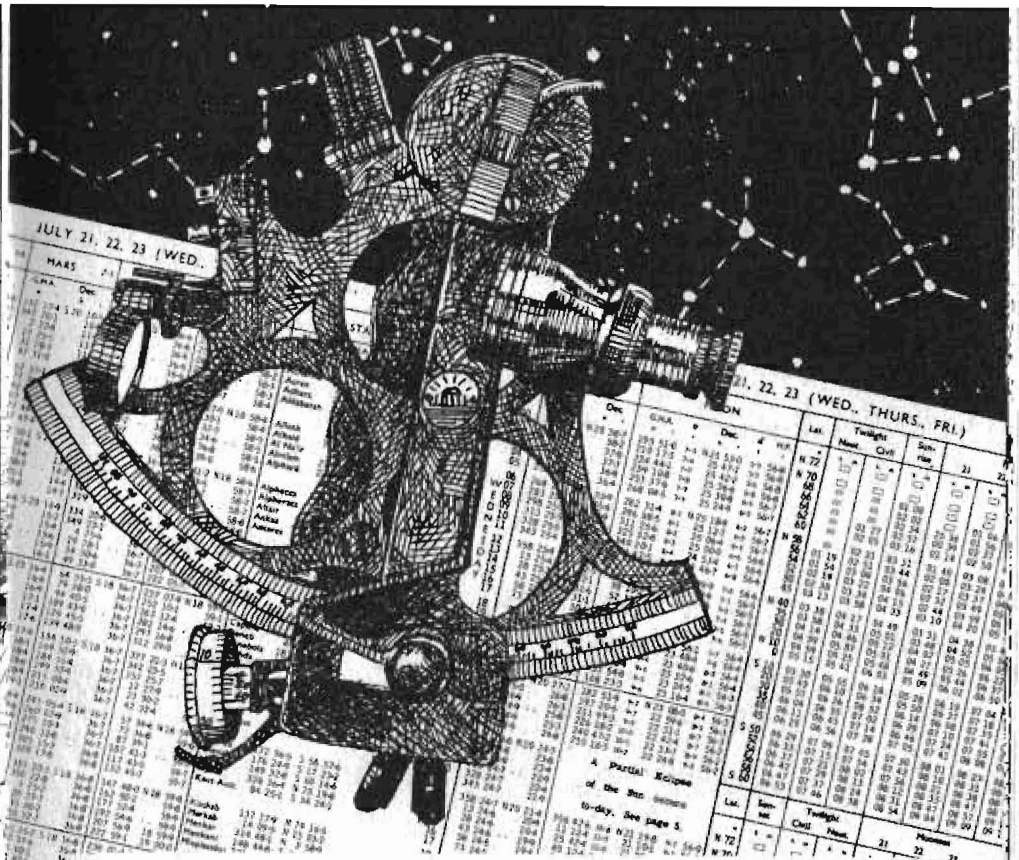
Over the next century refinements led in 1889 to Siegmund Riefler's clock with a nearly free pendulum, which attained an accuracy of a hundredth of a second a day and became the standard in many astronomical observatories. A true free-pendulum principle was introduced by R. J. Rudd about 1898, stimulating development of several free-pendulum clocks. One of the most famous, the W. H. Shortt clock, was demonstrated in 1921. The Shortt clock almost immediately replaced Riefler's clock as a supreme timekeeper in many observatories. This clock consists of two pendulums, one a slave and the other a master. The slave pendulum gives the master pendulum the gentle pushes needed to maintain its motion, and also drives the clock's hands. This allows the master pendulum to remain free from mechanical tasks that would disturb its regularity.

Quartz Clocks

The Shortt clock was replaced as the standard by quartz crystal clocks in the 1930s and '40s, improving timekeeping performance far beyond that of pendulum and balance-wheel escapements.

Quartz clock operation is based on the *piezoelectric* property of quartz crystals. If you apply an electric field to the crystal, it changes its shape, and if you squeeze it or bend it, it generates an electric field. When put in a suitable electronic circuit, this interaction between mechanical stress and electric field causes the crystal to vibrate and generate a constant frequency electric signal that can be used to operate an electronic clock display.

Quartz crystal clocks were better because they had no gears or escapements to disturb their regular frequency. Even so, they still relied on a mechanical vibration whose frequency depended critically on the crystal's size and shape. Thus, no two crystals can be precisely alike, with exactly the same frequency. Such quartz clocks continue to dominate the market in numbers because their performance is excellent and they are inexpensive. But the timekeeping performance of quartz clocks has been substantially surpassed by atomic clocks.



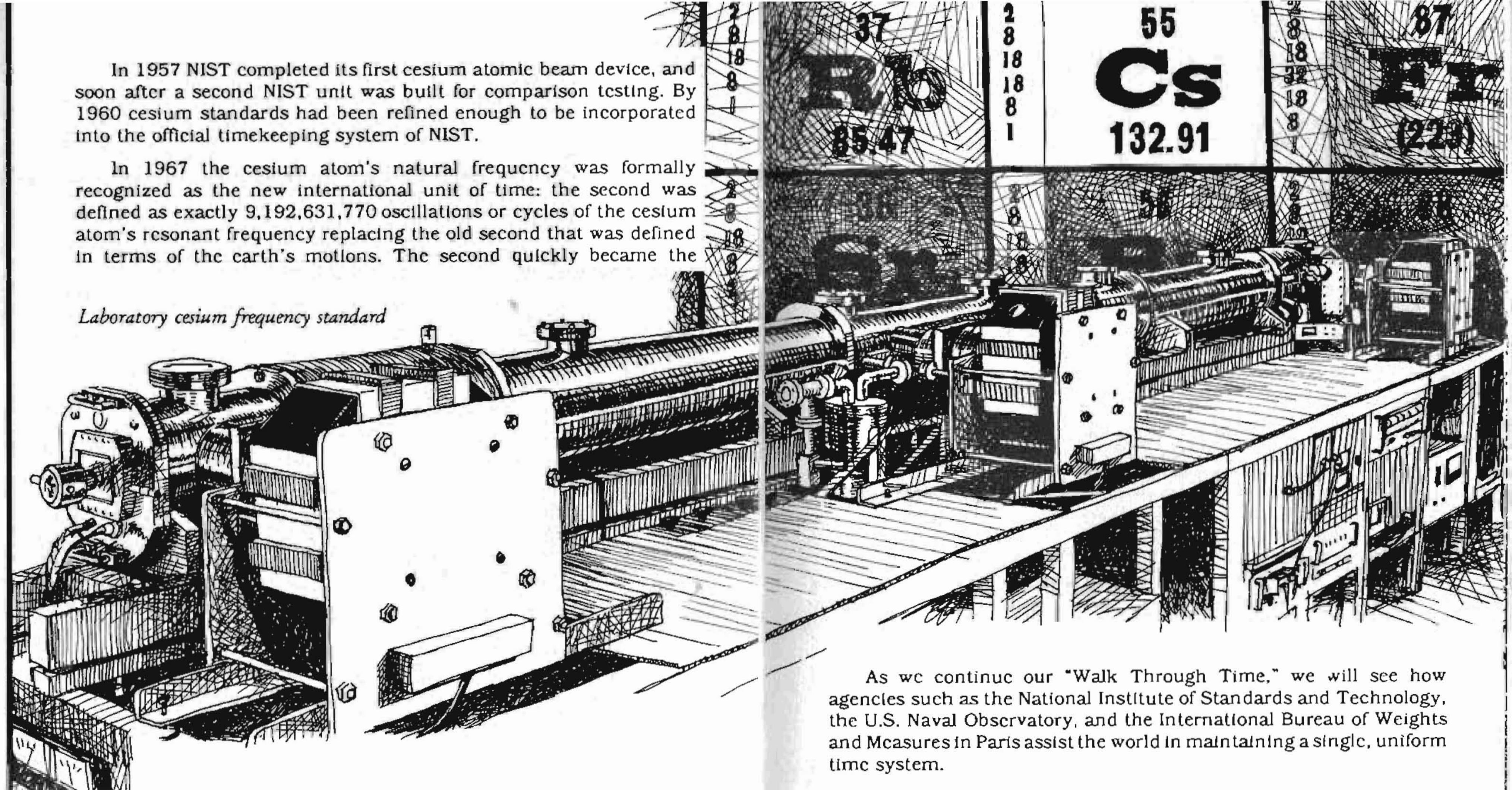
The "Atomic" Age of Time Standards

Scientists had long realized that atoms (and molecules) have resonances; each chemical element and compound absorbs and emits electromagnetic radiation at its own characteristic frequencies. These resonances are inherently stable over time and space. An atom of hydrogen or cesium here today is exactly like one a million years ago or in another galaxy. Here was a potential "pendulum" with a reproducible rate that could form the basis for more accurate clocks.

The development of radar and extremely high frequency radio communications in the 1930s and '40s made possible the generation of the kind of electromagnetic waves (microwaves) needed to interact with the atoms. Research aimed at developing an atomic clock focused first on microwave resonances in the ammonia molecule. In 1949 NIST built the first atomic clock, which was based on ammonia. However, its performance wasn't much better than existing standards, and attention shifted almost immediately to more-promising, atomic-beam devices based on cesium.

In 1957 NIST completed its first cesium atomic beam device, and soon after a second NIST unit was built for comparison testing. By 1960 cesium standards had been refined enough to be incorporated into the official timekeeping system of NIST.

In 1967 the cesium atom's natural frequency was formally recognized as the new international unit of time: the second was defined as exactly 9,192,631,770 oscillations or cycles of the cesium atom's resonant frequency replacing the old second that was defined in terms of the earth's motions. The second quickly became the physical quantity most accurately measured by scientists. The best primary cesium standards now keep time to about one-millionth of a second per year.



Laboratory cesium frequency standard

Much of modern life has come to depend on precise time. The day is long past when we could get by with a timepiece accurate to the nearest quarter hour. Transportation, communication, manufacturing, electric power and many other technologies have become dependent on super-accurate clocks. Scientific research and the demands of modern technology continue to drive our search for ever more accurate clocks. The next generation of cesium time standards is presently under development at NIST's Boulder laboratory and other laboratories around the world.

As we continue our "Walk Through Time," we will see how agencies such as the National Institute of Standards and Technology, the U.S. Naval Observatory, and the International Bureau of Weights and Measures in Paris assist the world in maintaining a single, uniform time system.

World Time Scales

In the 1840s a Greenwich standard time for all of England, Scotland, and Wales was established, replacing several "local time" systems. The Royal Greenwich Observatory was the focal point for this development because it had played such a key role in marine navigation based upon accurate timekeeping. Greenwich Mean Time (GMT) subsequently evolved as the official time reference for the world and served that purpose until 1972.

The United States established the U.S. Naval Observatory (USNO) in 1830 to cooperate with the Royal Greenwich Observatory and other world observatories in determining time based on astronomical observations. The early timekeeping of these observatories was still driven by navigation. Timekeeping had to reflect changes in the earth's rotation rate; otherwise navigators would make errors. Thus, the USNO was charged with providing time linked to "earth" time, and other services, including almanacs, necessary for sea and air navigation.

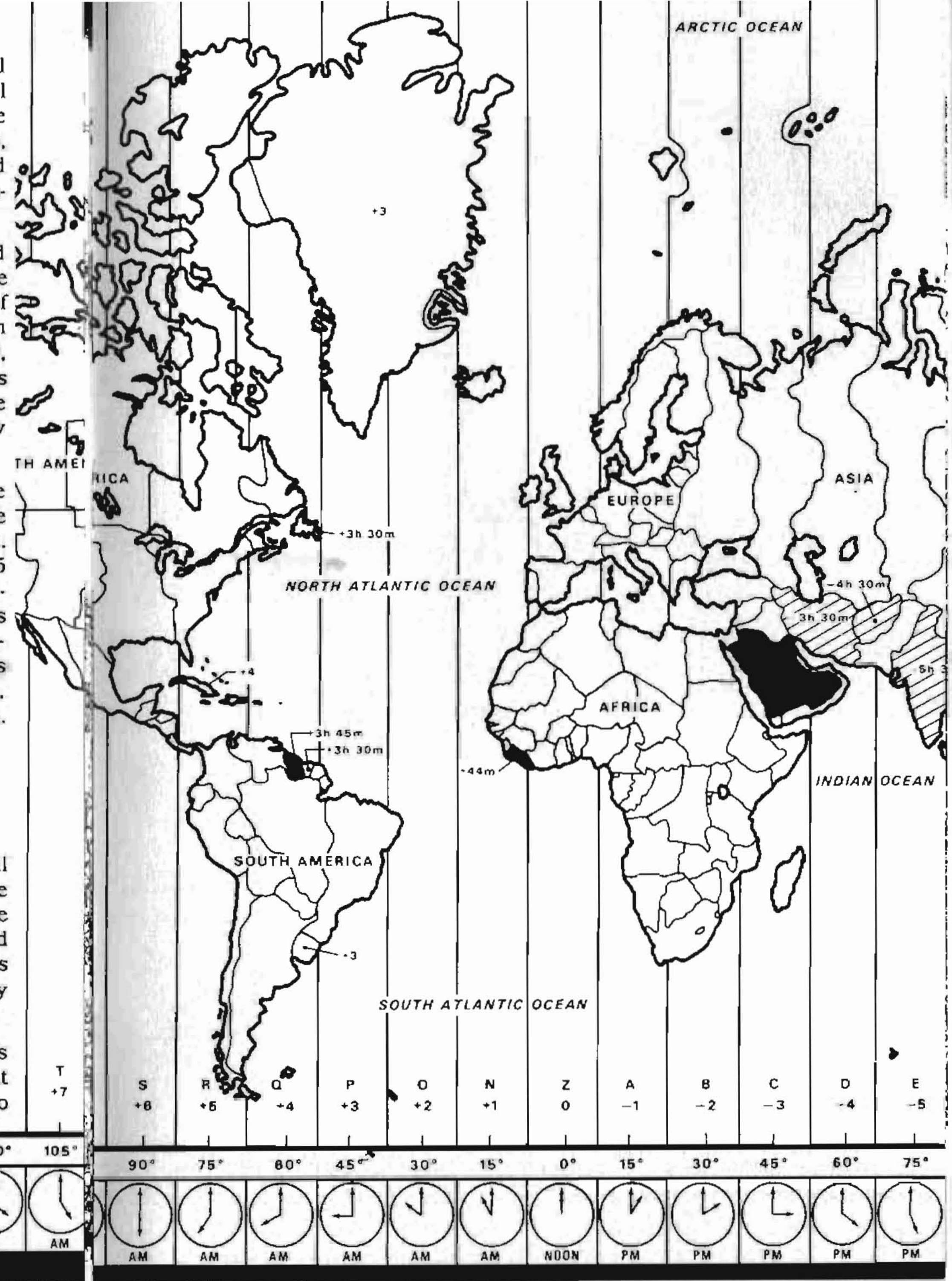
With the advent of highly accurate atomic clocks, scientists and technologists recognized the inadequacy of timekeeping based on the motion of the earth which fluctuates in rate by a few thousandths of a second a day. The redefinition of the second in 1967 had provided an excellent reference for more accurate measurement of time intervals, but attempts to couple GMT (based on the earth's motion) and this new definition proved to be highly unsatisfactory. A compromise time scale was eventually devised, and on January 1, 1972, the new Coordinated Universal Time (UTC) became effective internationally.

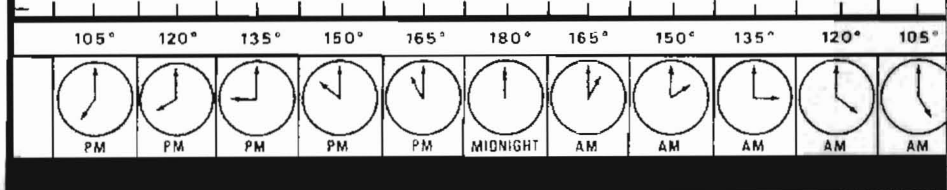
UTC runs at the rate of the atomic clocks, but when the difference between this atomic time and one based on the earth approaches one second, a one-second adjustment (a "leap second") is made in UTC. NIST's clock systems and other atomic clocks located in more than 25 countries now contribute data to the international UTC scale coordinated in Paris by the International Bureau of Weights and Measures (BIPM). An evolution in timekeeping responsibility from the observatories of the world to the measurement standards laboratories has naturally accompanied this change from "earth" time to "atomic" time. But there is still a needed coupling, the leap second, between the two.

The World's Time Zones

Time zones did not become necessary in the United States until trains made it possible to travel hundreds of miles in a day. Until the 1860s most cities relied upon their own local "sun" time, but this time changed by approximately one minute for every 12½ miles traveled east or west. The problem of keeping track of over 300 local times was overcome by establishing railroad time zones. Until 1883 most railway companies relied on some 100 different, but consistent, time zones.

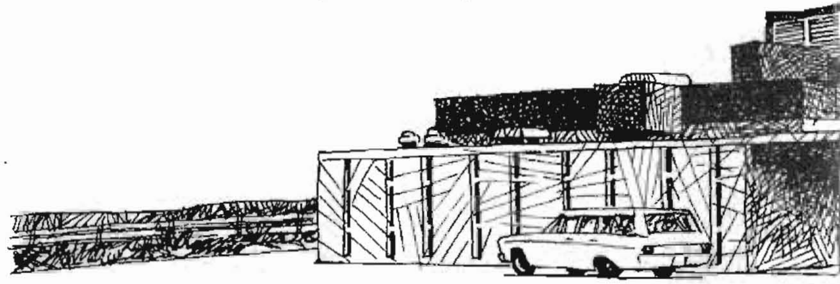
That year, the United States was divided into four time zones roughly centered on the 75th, 90th, 105th, and 120th meridians. At noon, on November 18, 1883, telegraph lines transmitted GMT time to





major cities where authorities adjusted their clocks to their zone's proper time.

On November 1, 1884, the International Meridian Conference in Washington, D. C., applied the same procedure to zones all around the world. The 24 standard meridians, every 15° east and west of 0° at Greenwich, England, were designated the centers of the zones. The international date line was drawn to generally follow the 180° meridian in the Pacific Ocean. Because some countries, islands and states don't want to be divided into several zones, the zones' boundaries tend to wander considerably from straight north-south lines.



NIST Time and Frequency Services

Since 1923 NIST radio station WWV has provided round-the-clock shortwave broadcasts of time and frequency signals. A sister station, WWVH, was established in 1948 in Hawaii. WWV's audio signal is also offered by telephone: dial (303) 499-7111 (not toll-free). A similar service from WWVH is available by dialing (808) 335-4363 in Hawaii.

Broadcast frequencies are 2.5, 5, 10, and 15 megahertz for both stations, plus 20 MHz on WWV. The signal includes UTC time in both voice and coded form; standard carrier frequencies, time intervals and audio tones; information about Atlantic or Pacific storms; geophysical alert data related to radio propagation conditions; and other public service announcements. Accuracies of one millisecond (one thousandth of a second) can be obtained from these broadcasts if one corrects for the distance from the stations (near Ft. Collins, Colorado, and Kauai, Hawaii) to the receiver. The telephone services provide time signals accurate to 30 milliseconds or better, which is the maximum delay in cross-country telephone lines.

In 1956 low-frequency station WWVB began broadcasting at 60 kilohertz. WWVB offers a direct path signal of greater accuracy than WWV or WWVH, but a special low-frequency receiver is required to decode the time signal.

Since 1975 NIST time and frequency signals have been relayed to most of the Western Hemisphere by satellites positioned high above the equator. The two GOES weather satellites operated by the National Oceanic and Atmospheric Administration broadcast a time code near 468 MHz that can set suitable clocks to within 100 microseconds (millionths of a second) of UTC time.

NIST also offers an Automated Computer Time Service (ACTS) that uses telephone lines to synchronize computer clocks to the NIST time standard. When connected to ACTS through a modem, a computer can display UTC time and date. The ACTS modem phone number is (303) 494-4774. If suitable software is installed (available from the address below*), a computer can receive timing signals from ACTS to set its internal clock. One mode of operation of the system provides automatic compensation for the delays in the telephone connection resulting in a time transfer accuracy of a few milliseconds.

More information about NIST time and frequency standards and activities can be obtained from:

Time and Frequency Division
NIST — 325 Broadway
Boulder, CO 80303
(303) 497-3276

* ACTS software, including model source code for a variety of DOS, UNIX, and VMS operating systems (and adaptable to other systems), is available for a fee from the address below. Specify Research Material #8101, Software for ACTS.

Office of Standard Reference Materials
NIST
Gaithersburg, MD 20899
(301) 975-6776

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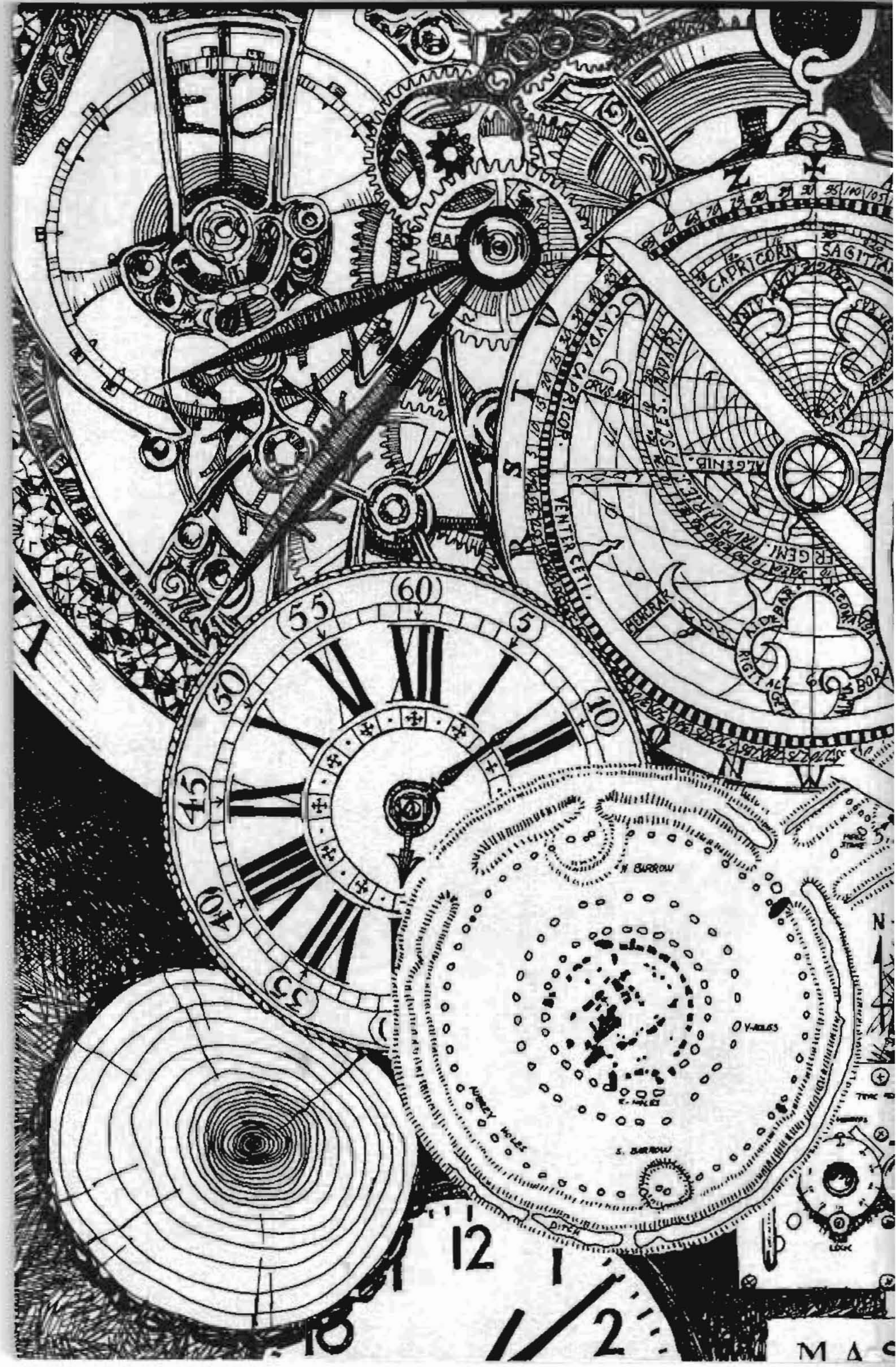
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